Impact of Body Composition on Intraperitoneal Pressure and Ultrafiltration in Peritoneal Dialysis

Alicia Sobrino-Pérez[a,b], Alfonso Pérez-Escudero[c], Luisa Sánchez-García[d], Sandra Sanz-Ballesteros[e], Carmen Felipe-Fernández[f], Esther Hernández-García[g], Victoria Oviedo-Gómez[g], Raquel de Toro-Casado[h], Astrid Rodríguez-Gómez[i], María José Fernández-Reyes-Luis[l], Vicente Pérez-Díaz[e,j]. On behalf of PIPDPCyL group.

(This article is a preprint and has not been peer-reviewed. It reports new medical research that has yet to be evaluated and so should not be used to guide clinical practice).

a Escuela de Doctorado, Universidad de Valladolid
b Departamento Medico, Fresenius Medical Care, Madrid
c CNRS, Université Paul Sabatier, Toulouse, France
d Servicio de Nefrología, Hospital Universitario Río Hortega, Valladolid
e Servicio de Nefrología, Hospital Clínico Universitario, Valladolid
f Servicio de Nefrología, Complejo Asistencial de Ávila
g Servicio de Nefrología, Complejo Asistencial Universitario de Palencia
h Servicio de Nefrología, Hospital Universitario de Burgos
i Servicio de Nefrología, Complejo Asistencial de Segovia
j Departamento de Medicina, Toxicología y Dermatología, Universidad de Valladolid
Autor para correspondencia: Vicente Pérez Díaz. E-mail: vperez5651@gmail.com. ORCID: https://orcid.org/0000-0001-8580-8954. Dirección Postal: Servicio de Nefrología Hospital Clínico Universitario de Valladolid. Av/ Ramón y Cajal, 3, 47003, Valladolid, España.

ABSTRACT

Introduction: An increase in body mass index (BMI) raises intraperitoneal pressure (IPP), which in turn counteracts ultrafiltration (UF). However, BMI is not directly associated with UF, contrary to what might be expected. We examined these relationships in greater depth by breaking down BMI into fat tissue index (FTI), lean tissue index (LTI), and overhydration (OHI), assessed by bioimpedance spectroscopy (BIS).

Methods: Two peritoneal equilibration tests (PETs) using 4.25%/3.86% dextrose (2 L and 1 L fill volumes) were performed in 76 unselected patients. IPP was measured repeatedly and BIS was conducted to calculate LTI, FTI, OHI and phase angle at 50 kHz (PhA).

Results: IPP increased with intraperitoneal volume (empty: 7.8 cmH_2O; 1 L: 10.3 cmH_2O; 2 L: 12.2 cmH_2O) and correlated negatively with UF. BMI correlated positively with IPP but not with UF. FTI correlated positively with BMI and IPP and negatively with UF. LTI did not correlate with BMI or IPP but correlated positively with UF. These relationships were mirrored in aquaporin-mediated free water transport (FWT). PhA mirrored LTI.

Conclusions: The effects of BMI on IPP and of IPP on UF appear to be mediated by FTI, whereas LTI independently enhances UF. Aquaporin-mediated FWT shows similar associations. Routine assessment of IPP and body composition may help identify patients at higher risk for IPP-related UF impairment.

KEYWORDS
Bioimpedance, intraperitoneal pressure, ultrafiltration, aquaporins, lean mass, fat mass, phase angle.

List of Abbreviations

BIS: Multifrequency bioimpedance spectroscopy. **BMI:** Body mass index. **D/P$_{\text{Creat}}$:** Dialysate-to-plasma creatinine concentration ratio in the final drain of the PET. **FTI:** Fat tissue index. **FVI:** *Fat volume index*—FTI expressed as the volume it occupies (L), rather than mass (kg). **FWT:** Free water transport. **[Gluc]$_{\text{D}}$:** Glucose concentration in the final drain of the PET. **IPP:** Intraperitoneal pressure. **IPPv:** Intraperitoneal pressure with an empty abdomen (mean of the six measurements obtained at baseline). **IPV:** Intraperitoneal volume. **LTI:** Lean tissue index **LVI:** *Lean volume index*—LTI expressed as the volume it occupies (L), rather than mass (kg). **Na-dip:** Decrease in dialysate sodium concentration at 60 minutes compared with baseline after infusion, in the 2-L PET. **OH:** Overhydration. **OHI:** Overhydration index. **PD:** Peritoneal dialysis. **PET:** Peritoneal equilibration test. **PET 1L:** Peritoneal equilibration test with a 1-liter fill volume. **PET 2L:** Peritoneal equilibration test with a 2-liter fill volume. **PhA:** Phase angle at 50 kHz in bioimpedance. **UF:** Ultrafiltration.

Impact of Body Composition on Intraperitoneal Pressure and Ultrafiltration in Peritoneal Dialysis

Introduction

In peritoneal dialysis (PD), elevated intraperitoneal pressure (IPP) contributes to mechanical complications (1–6), influences patient and technique prognosis (1,7), and significantly reduces ultrafiltration (UF) (8–11). Understanding the factors that modulate IPP may therefore help mitigate its clinical impact. Infusing dialysate into the closed peritoneal cavity increases IPP by approximately 2.2 cmH_2O per liter (2,4). However, IPP with an empty abdomen already shows wide interpatient variability (1–18 cmH_2O) (10,12), largely explained by its correlation with body mass index (BMI), which accounts for up to 27% of this variability (1,3,4,10–16).

BMI is a convenient indicator of body size but does not differentiate between adiposity, muscularity, or—in PD—fluid overload. Multifrequency bioimpedance spectroscopy (BIS) allows decomposition of body composition into lean mass, fat mass and overhydration, providing a more accurate characterization (17).

In this study, we examined the relationship of body size and composition with IPP, and how these components influence UF and aquaporin-mediated free water transport (FWT), given their physiological interconnection. To do this, we expanded a previous study (12) using two PETs (4.25%/3.86% dextrose) with different fill volumes to generate comparable exchanges except for IPP. In four of six participating PD units, BIS was also performed at the start of each PET; this report presents the findings from that subgroup.

Methods

Between 2017 and 2019, unselected adult patients from five PD units underwent two standard PETs (4 h, 4.25%/3.86% dextrose), performed in random order one week apart: one using the usual fill volume of 2000 mL (PET 2L) and the other using 1000 mL (PET 1L), in order to generate different IPP levels under otherwise identical conditions (12). Both PETs were performed in the supine position by regular PD nursing staff. At the start of each PET, body composition was assessed using BIS. IPP was measured before and after each infusion and drainage (0, 60, and 240 minutes), both with an empty abdomen and with the abdomen filled, in which case the corresponding intraperitoneal volume (IPV) was recorded. Fill and drain volumes were measured by weight (1 g = 1 mL).

Sex, age, medical history, and PET-related parameters were documented. The dialysate/plasma creatinine ratio at 240 minutes (D/P_{Creat}) was used as a marker of peritoneal transport. UF insufficiency was defined as net UF < 400 mL during the PET 2L (18), and impaired aquaporin-mediated free water transport (impaired FWT) was defined, also in the PET 2L, as a decrease in intraperitoneal sodium concentration at 60 minutes (Na-Dip) ≤ 5 mEq/L relative to baseline (18).

Before each PET, after 15 minutes in the supine position with an empty abdomen, body composition was assessed using the Body Composition Monitor (BCM®, Fresenius Medical Care, Bad Homburg, Germany), a three-compartment BIS model. This provided the lean tissue index (LTI) and fat tissue index (FTI), expressed in kg/m^2 (with m^2 referring to height squared), as well as total body overhydration (OH) (17). To ensure height-adjusted values, we derived the overhydration index (OHI) by dividing OH by height squared. To account for both mass and volume components of BMI, we estimated the volume occupied by fat tissue (density 0.925–0.970 g/mL (19)) and lean tissue (density 1.10 g/mL (20)), which we termed the fat volume index

(FVI) and lean volume index (LVI), respectively. Phase angle at 50 kHz (PhA) was also recorded. BMI, body composition parameters and phase angle used in the analyses correspond to the mean of the measurements obtained in both PETs, as no significant differences were observed between them.

Direct IPP measurements were obtained using a central venous pressure manometry system (12,21,22), connected via a three-way stopcock placed between the PD catheter and the double-bag system. The zero reference point was set at the mid-axillary line. Once the rise of the fluid column stabilized and respiratory oscillations were confirmed, IPP was recorded as the midpoint of a normal oscillation. For analysis, we used the mean of the six measurements taken with an empty abdomen (IPPv). Although IPP may vary over time, such variation is generally minimal when measurements are performed within a 7-day interval (21).

The study protocol was approved by the Clinical Research Ethics Committee of the Valladolid-East Health Area (CEIC-VA-ESTE-HCUV-PI 17-657).

Continuous variables are expressed as mean ± standard deviation and range, and categorical variables as absolute values and percentages, unless otherwise specified. Comparisons of continuous variables were performed using independent or paired Student’s t-tests, and Pearson’s correlation coefficient (r) was used to assess linear associations. All tests were two-tailed, and p values <0.05 were considered statistically significant. Multivariate analyses were conducted using linear or logistic regression models, as appropriate. Collinearity among independent variables was evaluated using tolerance and variance inflation factor (VIF), with tolerance >0.1 and VIF <10 considered acceptable. Statistical analyses were performed using Microsoft Excel (Office 365) and IBM SPSS Statistics version 25.

Results

A total of 87 patients were studied: 61 (70%) were men, with a mean age of 62 ± 14 years (range 25–89), and a median PD vintage of 14 ± 17 months (range 1–75). Forty-eight patients (56%) were on automated peritoneal dialysis (APD) and 38 (44%) on continuous ambulatory peritoneal dialysis (CAPD). Nine patients had polycystic kidney disease, and six had a non-functioning renal graft.

The main results of the 2L and 1L PETs are shown in Table 1. Peritoneal transport characteristics from the 2L PET were as follows: high transport (0.82 < D/PCreat < 1.01) in 16 patients (18%), high-average ($0.68 < D/P_{Creat} < 0.82$) in 54 patients (62%), and low-average ($0.50 < D/P_{Creat} < 0.68$) in 17 patients (20%). The 2L PET produced higher IPP values, lower peritoneal transport rates, and higher final dialysate glucose concentrations ($[Gluc]_D$) and UF (Table 1).

Body composition

Body composition parameters FTI and LTI are shown in Table 1 both as mass (kg/m²) and as volume (FVI and LVI, in L/m²). None of the correlations or comparisons showed significant differences between using mass-based or volume-based indices; therefore, only the mass-based results are presented here, as they represent the more conventional approach.

Table 1. Patients characteristics and body composition, intraperitoneal pressure and PET results with 2L and 1L

n (%)	87 (100%)
Age (years)	62±14 (25-89)
Months in PD	14±17 (1-75)
BMI (kg/m^2)	26,4±4,2 (16,6-40)
LTI (kg/m^2)	15,2±3,7 (7,8-25)
LVI (L/m^2)	13,8±3,4 (7,1-22,7)
FTI (kg/m^2)	10,7±5,7 (1,4-30,2)
FVI (L/m^2)	11,1±5,8 (1,5-31,4)
OH (L)	1,3±1,9 (-1,8-5,7)
OHI (Kg/m^2 - L/m^2)	0,5±0,7 (-0,7-2)
PhA (º)	5,26±1,14 (2,38-8,15)
IPPv (cmH_2O)	8,0±2,9 (1,3-15)
IPP full, 0 min, PET 2L (cmH_2O)	12,3±3,6 (4,5-20,5)
	p <0,001
IPP full, 0 min, PET 1L (cmH_2O)	10,3±3,0 (3-19)
IPP full, 240 min, PET 2L (cmH_2O)	13,1±3,5 (6-24,5) *
	p <0,001
IPP full, 240 min, PET 1L (cmH_2O)	11,1±3,5 (4,5-21) *
$D/P_{Creat,}$ PET 2L	0,73±0,10 (0,52-1,00)
	p <0,001
$D/P_{Creat,}$ PET 1L	0,78±0,11 (0,51-1,02)
$[Glucose]_D$ 240 min, PET 2L (mg/dL)	928±250 (436-1512)
	p <0,001
$[Glucose]_D$ 240 min, PET 1L (mg/dL)	633±192 (240-1051)
Na-Dip PET 2L (mmol/L)	6,5±3,2 (0-14)
	p = 0,002
Na-Dip PET 1L (mmol/L)	4,9±3,8 (-1-16)
UF, PET 2L (mL)	672±302 (-82-1575)
	p <0,001
UF, PET 1L (mL)	463±250 (-200-1216)

Definitions: BMI: body mass index; LTI: lean tissue index; LVI: lean volume index; FTI: fat tissue index; FVI: fat volume index; OH: overhydration; OHI: overhydration index; PhA: Phase angle at 50 kHz; IPPv: intraperitoneal pressure with empty abdomen; D/P_{Creat}: dialysate/plasma creatinine ratio at 240 minutes; $[Glucose]_D$: dialysate glucose concentration at 240 minutes; Na-Dip: sodium dip at 60 min vs. 0 min; UF: ultrafiltration. *p < 0.05 paired t-test comparing IPP full at 0 vs. 240 min.

In our cohort, BMI correlated only with FTI ($r = 0.682$, $p < 0.01$) and not with LTI ($r = 0.041$, $p = 0.724$) or OHI ($r = 0.035$, $p = 0.755$) (Figure 1). FTI showed a negative correlation with LTI ($r = –0.676$, $p < 0.01$). PhA was unrelated to BMI but was associated with its components: positively with LTI ($r = 0.680$, $p < 0.001$) and negatively with FTI ($r = –0.295$, $p = 0.013$) and OHI ($r = –0.578$, $p < 0.001$).

Relationship with IPP

IPPv correlated positively with BMI ($r = 0.552$, $p < 0.001$), with BMI accounting for 31% of its variability ($r^2 \times 100$) (Figure 2). IPPv also correlated with FTI ($r = 0.465$, $p < 0.001$), which explained 22% of the variation in IPPv. No significant correlations were observed between IPPv and LTI ($r = –0.097$, $p = 0.407$), OHI ($r = 0.132$, $p = 0.233$), or PhA ($r = –0.020$, $p = 0.856$) (Figure 2). In multivariate analysis, all three body composition components influenced IPP, with FTI showing the greatest relative effect (Table 2).

IPP increased with infused volume (Table 1). FTI correlated positively with the increment in IPP associated with the rise in intraperitoneal volume from 1 to 2 L ($r = 0.246$, $p = 0.036$), but not with the increase from 0 to 1 L ($r = –0.036$, $p = 0.764$) or from 0 to 2 L ($r = 0.105$, $p = 0.367$).

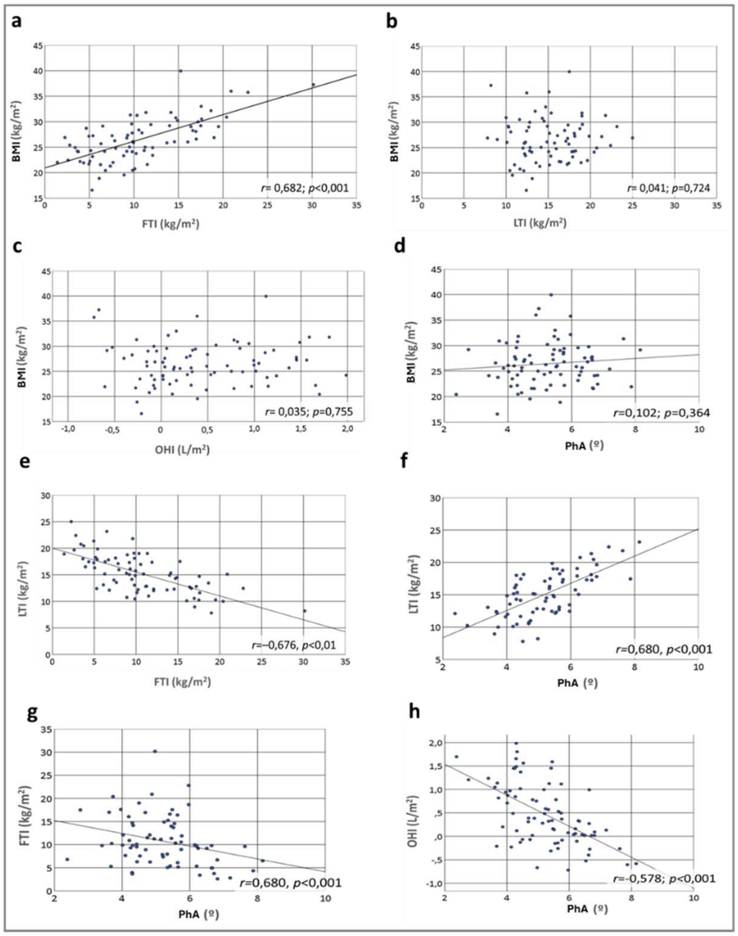

Figure 1. Relation between body composition components, phase angle and body mass index (a,b,c,d), between lean an fat tissue index (d) and between phase angle and body composition components (LTI, FTI, OHI) (f, g, h). BMI: body mass index. FTI, fat tissue index; LTI, lean tissue index; OHI, overhydration index. PhA: phase angle at 50 kHz.

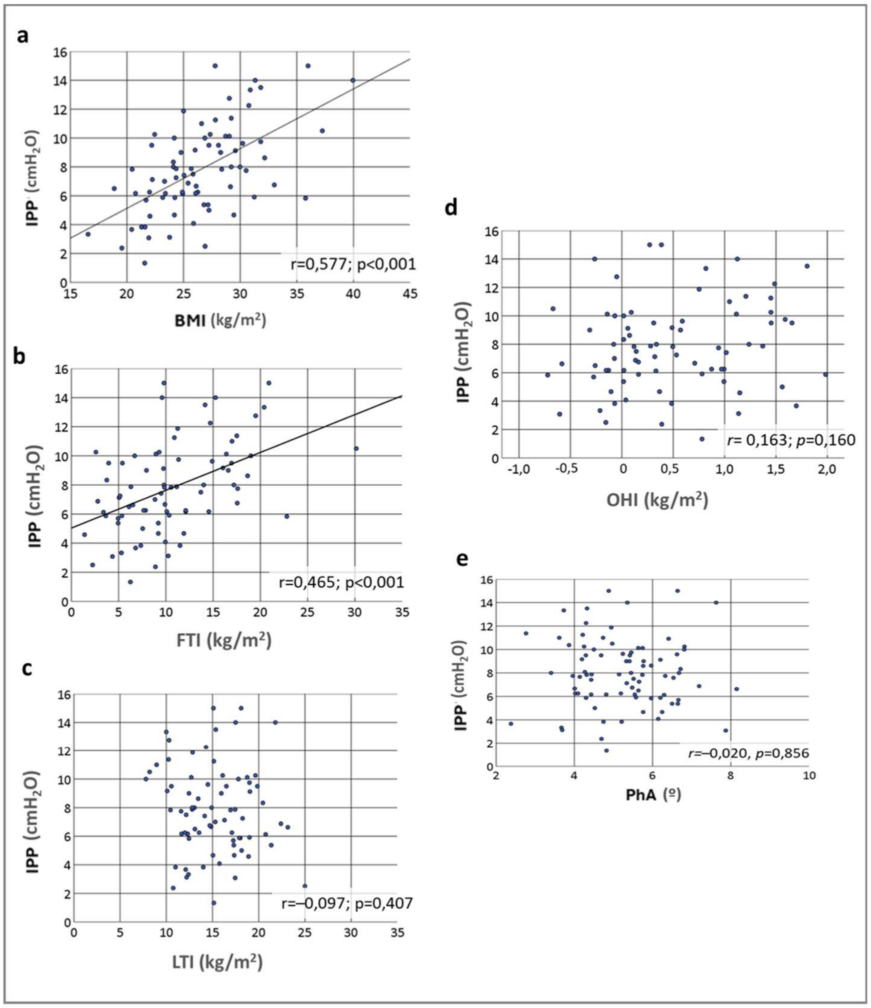

Figure 2. Relationship between intraperitoneal pressure with an empty abdomen and body mass index (a), and between intraperitoneal pressure and body composition components (b, c, d) and phase angle (e). IPP: intraperitoneal pressure with an empty abdomen. BMI: body mass index. Body composition components: FTI, fat tissue index; LTI, lean tissue index; OHI, overhydration index. PhA, phase angle.

Table 2. Linear regression for intraperitoneal pressure with an empty abdomen

	Std. Coeff. β	p
LTI	0,482	<0,001
FTI	0,768	<0,001
OHI	0,268	0,005

Linear regression analysis of body composition components on mean intraperitoneal pressure with an empty abdomen (IPPv), adjusted for phase angle. LTI: lean tissue index; FTI: fat tissue index; OHI: overhydration index. Standardized coefficients (Std.Coeff) (β) and statistical significance (p-values) are reported. In all models, collinearity indices met acceptable thresholds: Tolerance >0.2 and VIF <5.

Relationship with Ultrafiltration

UF correlated negatively with IPPv in the 2-L PET (r = –0.267, p = 0.012), with the same nonsignificant trend in the 1-L PET (r = –0.198, p = 0.067) (Figure 3). BMI showed no relationship with UF in either PET (2-L PET: r = –0.049, p = 0.655; 1-L PET: r = –0.139, p = 0.198). FTI correlated negatively with UF in the 1-L PET (r = –0.244, p = 0.034) and showed a similar but not significant tendency in the 2-L PET (r = –0.221, p = 0.056). LTI correlated positively with UF in both PETs (2-L PET: r = 0.267, p = 0.020; 1-L PET: r = 0.256, p = 0.026), as did PhA (2-L PET: r = 0.237, p = 0.032; 1-L PET: r = 0.299, p = 0.006). No correlations were found with OHI. (Figure 3)

Multivariate analyses identified LTI, OHI, IPPv, and D/P_{Creat} as determinants of UF in the 2-L PET; in the 1-L PET, LTI, IPPv, and D/P_{Creat} were significant. (Table 3).

Na-Dip in the 2-L PET, correlated negatively with IPPv (r = –0.241, p = 0.026), with FTI (r = –0.334, p = 0.003), and with D/P_{Creat} (r = –0.299, p = 0.005), and positively with LTI (r = 0.251, p = 0.030). No correlation were found with OHI or PhA; however, in multivariate analysis, both PhA and OHI emerged as additional influences on Na-Dip in the 2-L PET, along with D/P_{Creat} and IPPv (Table 3).

In the 1-L PET, Na-Dip showed no relationship with IPPv or with any body composition component or PhA. A negative correlation was observed with D/P_{Creat} (r = –0.462, p < 0.001) and a positive correlation with $[Gluc]_D$ (r = 0.476, p < 0.001), with the latter being the only variable that remained significant in the multivariate analysis (Table 3).

Table 3. Multivariable linear regression for ultrafiltration and Na-Dip in the 2-L and 1-L PETs

		Std. Coeff. β	**p**
UF, PET 2L	**D/P_{Creat} PET 2L**	-0,502	<0,001
	IPPv	-0,428	0,004
	LTI	0,594	<0,001
	FTI	0,297	0,057
	OHI	0,284	0,040
UF, PET 1L	**D/P_{Creat} PET 1L**	-0,424	<0,001
	IPPv	-0,233	0,031
	LTI	0,329	0,003
Na-Dip, PET 2L	**D/P_{Creat} PET 2L**	-0,336	0,010
	IPPv	-0,254	0,030
	OHI	0.332	0,038
	PhA	0,347	0,019
Na-Dip, PET 1L	**$[Gluc]_D$**	0,516	<0,001

LTI: lean tissue index; FTI: fat tissue index; OHI: overhydration index; IPPv: mean intraperitoneal pressure with an empty abdomen; D/PCreat: dialysate-to-plasma creatinine ratio at 240 minutes; [Gluc]D: dialysate glucose concentration at 240 minutes; PhA: phase angle at 50 kHz. All models were adjusted for D/PCreat, [Gluc]D, Na-Dip in the corresponding PET, IPPv, LTI, FTI, and OHI. Standardized coefficients (Std Coeff.) (β) and p-values are reported. Collinearity indices were within acceptable limits (Tolerance >0.2; VIF (variance inflation factor) <5).

A total of 17 patients (19.5%) presented UF insufficiency, and 32 (38%) exhibited impaired aquaporin-mediated FWT. These patients showed higher IPPv, higher D/P_{Creat}, older age, higher FTI and BMI, and lower LTI and PhA (Table 4), although only differences in age and FTI were statistically significant in patients with impaired FWT.

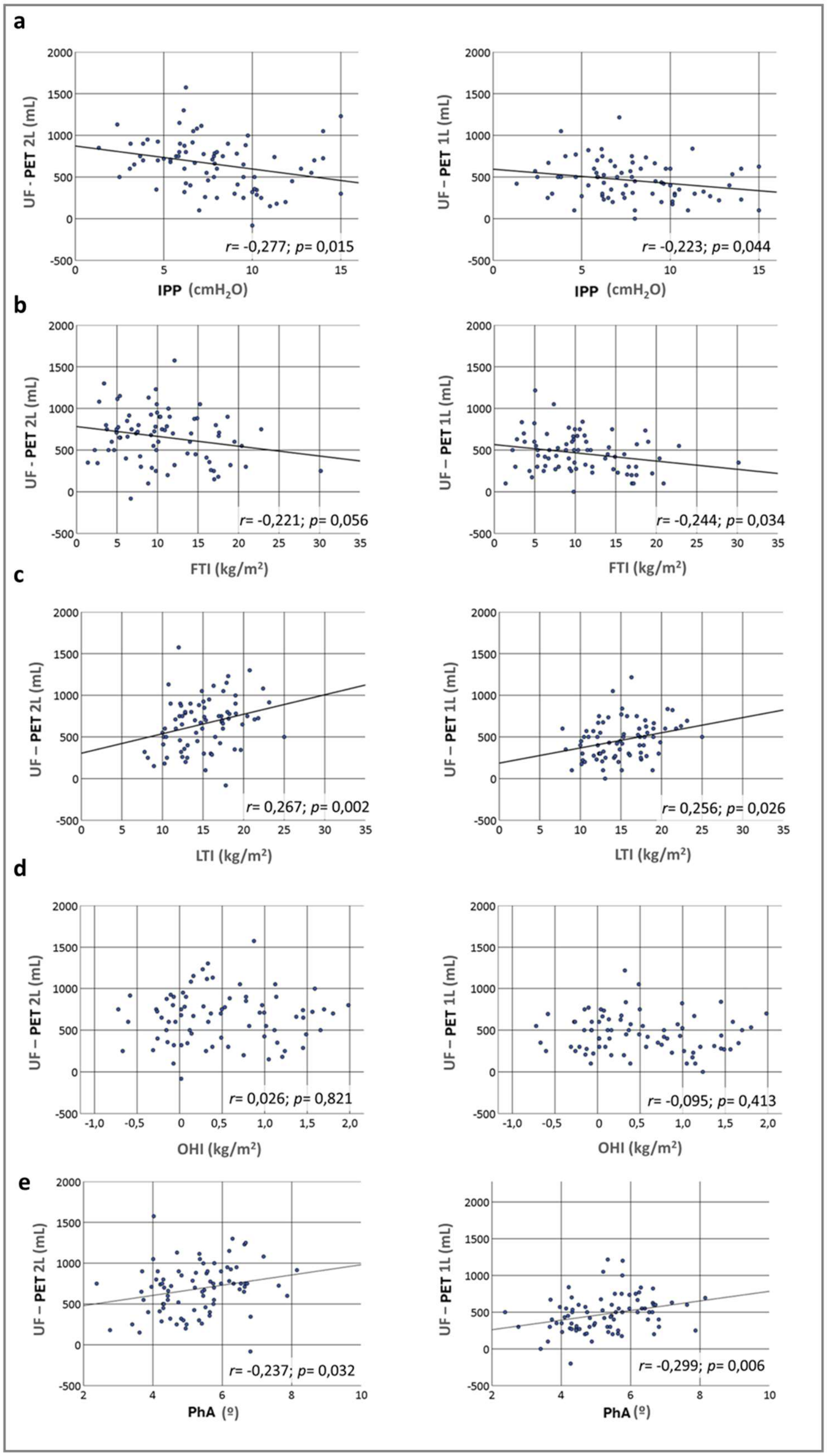

Figure 3. Relationship of ultrafiltration during the 2-L and 1-L PET with intraperitoneal pressure with an empty abdomen (a), body composition components (b, c, d), and phase angle (e). IPP: intraperitoneal pressure with an empty abdomen. BMI: body mass index. Body composition components: FTI, fat tissue index; LTI, lean tissue index; OHI, overhydration index. UF: ultrafiltration. PET: peritoneal equilibration test; PhA: phase angle at 50 kHz.

Table 4. Characteristics of patients with and without ultrafiltration insufficiency or aquaporin-mediated free-water transport impairment

	UFI	p	No-UFI	Impaired FWT	p	No-Impaired FWT	UFI and/or Impaired FWT	p	No UFI and/or Impaired FWT
n (%)	17 (19,5%)	-	70 (80,5%)	32 (38%)	-	55* (62%)	38 (45%)	-	48* (55%)
Age	65±9	0,126	61±15	67±10	0,004	59±15	67±10	0,002	58±15
Months PD	20±21	0,112	12±16	13±15	0,671	15±19	14±17	0,985	14±18
Residual D.	1622±823	0,985	1627±877	1619±823	0,996	1618±897	1592±811	0,802	1640±914
BMI (kg/m²)	26,9±4,3	0,581	26,3±4,2	27,6±4,5	0,040	25,7±3,9	27,5±4,3	0,049	25,7±4,0
LTI (kg/m²)	13,4±3,6	0,022	15,7±3,6	14,2±3,8	0,048	15,8±3,4	14,2±3,8	0,034	16,0±3,3
FTI (kg/m²)	13,2±7,2	0,096	10±4,8	12,9±5,5	0,005	9,3±5,1	12,5±5,8	0,006	9,1±4,7
OHI (kg/m²)	0,4±0,6	0,794	0,5±0,7	0,5±0,6	0,345	0,4±0,7	0,6±0,6	0,167	0,4±0,7
PhA (º)	4,86±1,14	0,133	5,35±1,37	5,00±1,04	0,098	5,41±1,18	4,95±1,09	0,043	5,47±1,14
D/P_{Creat}	0,80±0,09	0,001	0,71±0,09	0,75±0,09	0,136	0,72±0,10	0,76±0,09	0,006	0,71±0,09
IPPv	9,3±2,5	0,023	7,5±3,0	9,0±3,1	0,003	7,2±2,7	9,1±2,9	<0,001	6,9±2,6

Table 4. Differences between patients with and without ultrafiltration insufficiency (UFI), and with and without impaired aquaporin-mediated free-water transport (FWT), according to PET results. Residual D.: residual diuresis in mL/24 h. BMI: body mass index. LTI: lean tissue index. FTI: fat tissue index. OHI: overhydration index. PhA: phase angle at 50 kHz. D/P_{Creat}: dialysate-to-plasma creatinine ratio at 240 minutes. IPPv: mean intraperitoneal pressure with an empty abdomen. Results are expressed as absolute values and percentages or as mean ± SD.

Discussion

IPP largely depends on BMI (1,3,4,10–15), although the mechanism linking both parameters has yet to be elucidated. Our study examines the impact of BMI and its individual components on IPP, as well as how this influence is reflected—with important nuances—in the effect of IPP on UF and its main determinant, aquaporin-mediated FWT.

We studied unselected PD patients to obtain results representative of routine clinical practice. IPP and body composition measurements were conducted during the PET, a test in which methodological care and precision are maximized within a clinical setting. We used the empty-abdomen IPP as the reference, as it is an intrinsic characteristic of each patient and is not influenced by intraperitoneal volume or by individual responses to it. To minimize the impact of measurement errors or transient variations, we used the mean of six measurements. Body composition assessed by BIS is well validated (17,23) and is increasingly used in PD units. BIS provides lean and fat mass both as absolute values and height-normalized indices (17); however, the BCM monitor expresses overhydration—relevant only in states of fluid overload—as a total body amount in liters or kilograms. To normalize it by height, similarly to the other components, we calculated an overhydration index (OHI) by dividing the value by height squared (m²). We also estimated the volume of each body component based on its density, to explore whether its potential effect depended on the space it occupied. The absence of differences between results expressed as mass or volume did not support this hypothesis. Therefore, we present only those obtained using mass values (LTI, FTI, and OHI in kg/m²). Additionally, we recorded the PhA at 50 kHz, a measurement shared by single- and multifrequency bioimpedance devices, which reflects nutritional status (24,25) and is associated with patient prognosis (25-28). PhA is calculated as the arctangent of the reactance-to-resistance ratio. In healthy adults, age, sex, and body mass index (BMI) are the main determinants of PhA. It has been shown that PhA is lower in hemodialysis patients compared with age and sex-matched healthy controls. However, the biological significance of PhA is not well defined in dialysis patients. PhA could be used for routine evaluation and detection of variations in nutritional and fluid status in patients with CAPD (26)

General considerations

Sex distribution, age, UF, transport characteristics, IPP values, body composition, PhA and BMI were within expected ranges for our PD population (11,26,29–33). As expected based on differences in intraperitoneal volume (IPV) (2,4), the 2-L PET produced higher IPP and delayed solute equilibration, reflected in lower D/P_{Creat} and higher $[Gluc]_D$ and UF (34–36).

Body composition

An increase in BMI is commonly observed after initiation of PD, primarily due to an increase in FTI (31,37,38). Although our cross-sectional design does not allow longitudinal interpretation, we observed a strong association between BMI and FTI, alongside a marked inverse correlation between FTI and both LTI and PhA. These findings suggest that in our cohort, higher BMI reflects adiposity rather than increased muscle mass—indeed, lean mass tended to decrease as adiposity increased. The moderate overhydration present in our cohort did not contribute meaningfully to BMI.

Relationship with IPP

A strong relationship exists between BMI and IPP (4,10,11,13), with BMI explaining approximately one-quarter of IPP variability (1,3,4,10–16). A key question is whether the clinical effects attributed to elevated IPP—mechanical complications (2–4,6), loss of residual renal function (5), technique failure and mortality (1,7), and reduced UF (10,11,39,40)—are mediated directly by IPP or instead reflect underlying body composition.

Our findings reaffirm that FTI is the principal body composition component influencing IPP, whereas LTI and OHI play comparatively minor roles (Table 2). The accumulation of adipose tissue may increase abdominal occupancy and raise IPP, much like larger fill volumes or polycystic kidney disease (10,14). Previous studies suggested that increased adiposity may contribute to poorer technique survival associated with high IPP (1,7), and our results reinforce this interpretation. The modest contributions of LTI and OHI in multivariate models may reflect the potential of muscle mass or tissue/interstitial edema to decrease abdominal compliance, thereby elevating IPP for a given IPV.

Relationship with ultrafiltration

The reduction in UF associated with elevated IPP (10,11,18,39,40) has traditionally been attributed to increased lymphatic and tissue absorption of dialysate (18,41), though IPP may also slow osmotic UF, particularly its aquaporin-mediated component (12). Despite the strong association between BMI and IPP, no relationship between BMI and UF has previously been described—and we likewise found none.

When separating BMI into its components, we did observe reduced UF with higher FTI in the 1-L PET and a nearly significant trend in the 2-L PET. This effect does not appear to be independent, as suggested by its loss of significance in multivariate regression, where IPP absorbed much of FTI's influence (Table 3). Conversely, LTI consistently favored UF in both PETs, as did PhA, a nutritional marker (25). This positive influence—previously unsuspected—was independent of IPP and accompanied the effects of the osmotic gradient in both PETs and IPP in the 2-L PET. These opposing influences of FTI and LTI may explain the absence of a direct relationship between BMI and UF despite the clear association between BMI and IPP. The beneficial association of LTI with UF aligns with observations of reduced UF in malnourished patients (42).

OHI showed a significant positive association with UF only in multivariate analysis, suggesting an independent contribution that becomes apparent only after adjusting for other factors (Table 3). Prior reports have linked pronounced overhydration with increased UF (43-45), though effects are harder to detect with milder overhydration, as in our cohort (10,12).

Free water transport (aquaporins) and Na-Dip

A previous study suggested that aquaporin-mediated FWT—assessed by Na-Dip in the 2-L PET—is negatively influenced by IPP (12). The present results, despite the smaller sample, reproduce this association. Although nephrologists traditionally attribute aquaporin function solely to osmotic gradients, in physiological systems -the osmotic gradient in PD is artificial and non-physiological-, aquaporins respond to both osmotic and hydrostatic forces (46–49). We also observed nutritional influences on Na-Dip: the negative association with FTI appears indirect and mediated by increased IPPv, while the positive associations with LTI and PhA lack an obvious physiological explanation, though animal studies suggest fasting modulates lipid metabolism while increasing aquaporin expression (22). These associations parallel those seen with net UF and merit future investigation.

Subgroups with UF impairment

Patients with UF insufficiency or impaired aquaporin-mediated FWT displayed features associated with reduced UF: higher IPPv, higher FTI, and lower LTI and PhA. Our previous work showed that in patients with UF abnormalities, increasing IPV from 1 to 2 L did not produce the expected slowing of the rate of IPP increase seen in patients without such abnormalities, resulting in higher final IPP. Body composition analysis now links the rate of IPP rise from 1 to 2 L to FTI.

LIMITATIONS

Several limitations must be considered. Although the study was conducted by trained PD nursing staff, procedures were performed within routine clinical practice rather than the tightly controlled conditions of a research environment. The cross-sectional design, limited sample size, and interdependence of variables constrain causal inference. The increase in IPP between 1 and 2 L was inferred from measurements obtained at baseline and at 60 and 240 minutes rather than continuous monitoring during infusion. Finally, results obtained with 4.25%/3.86% solutions may not be directly extrapolable to standard 1.5%/1.36% solutions, although some effects observed here might be even more pronounced under routine PD conditions with concentrations closer to 1.5%/1.36%.

Our aim was to achieve a clearer understanding of the factors that modulate IPP in PD, in order to identify patients and clinical situations at higher risk of elevated IPP and to provide tools for diagnosing and managing the resulting complications. One of the most immediate consequences is a reduction in UF, either through increased peritoneal reabsorption or through a slowing of osmotic UF and aquaporin-mediated FWT. Recognizing that body size is one of the determinants of IPP, we used BIS to break it down into its components and examine their relationships with IPP and UF. In doing so, we identified fat mass—i.e., obesity—as the main determinant of IPP and of its impact on UF. We also found an opposing effect of lean mass (and, similarly, of PhA, which has comparable nutritional significance), which enhances UF independently of IPP. This opposing influence of FTI and LTI on UF may help explain the absence of a direct correlation between BMI and UF in PD. Moreover, we observed that both indices, fat and lean, exert the same respective effects on aquaporin-mediated transport as they do on net UF.

Conclusions

Our findings confirm that in PD patients, the effect of BMI on IPP is mediated by FTI: it is adiposity—not increased muscle mass—that raises IPP. We also confirm the negative influence of IPP on UF and aquaporin-mediated FWT, as well as the absence of a direct association between BMI and UF despite BMI's influence on IPP. This paradox appears to reflect opposing effects of FTI (reducing UF via increased IPP) and LTI (enhancing UF independently of IPP). These associations warrant further study. Our results support routine assessment of IPP and body composition as part of standard PD care.

Acknowledgments

The authors thank Secundino Cigarrán-Guldris for his insights and explanations regarding bioelectrical impedance and phase angle, which broadened and clarified the interpretation of our results.

Author Contributions

ASP and VPD contributed to all aspects of the manuscript. ASP conceived and designed the study with substantial input from VPD. Under VPD's leadership, the design, methodological supervision, and data collection and processing were conducted by ASP, LSG, SSB, CFF, EHG, VOG, RTC, ARC, and MJFRL. Under the direction of Lucila Fernández Arroyo, PD nurses Olga Vegas Prieto, Ana Dorado García, María Bernárdez Lemus, Berta Martín Alcón, Carmen Gutiérrez Martín, María Jesús Vega García, Carmen Sánchez Fonseca, and Cristina Barrios Rebollo jointly developed the methodology and carried out the experimental procedures. APE performed the data analysis, which was interpreted by VPD, ASP, and APE. VPD, ASP, and APE conceived the tables and figures and wrote the manuscript, which was critically reviewed and approved by all co-authors and by all members of the group.

Declarations

Ethical Considerations

The treatment protocol complied with the Declaration of Helsinki and was approved by the Clinical Research Ethics Committee of the Valladolid-East Health Area (CEIC-VA-ESTE-HCUV – PI 17-657) and by the Research Committees of the University Clinical Hospital of Valladolid, Hospital Río Hortega of Valladolid, and the Complejos Asistenciales Universitarios of Palencia, Segovia, Ávila, and Burgos, all in Spain.

Consent to Participate

All patients provided written informed consent prior to participation in the study.

Consent for Publication

All patients provided written informed consent for the anonymous publication of their data in this study.

Conflict of Interest Statement

ASP is an employee of the Medical Department of Fresenius Medical Care, Spain. All other authors declare that they have no competing interests.

Funding Statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Authors' Note

Other members of the PIPDPCyL Group for the study of intraperitoneal pressure in peritoneal dialysis include PD nurses: Lucila Fernández-Arroyo, Olga Vegas-Prieto, Ana Dorado-García, María Bernández-Lemus, Berta Martín-Alcón, Carmen Gutiérrez-Martín, María Jesús Vega-García, Carmen Sánchez-Fonseca, and Cristina Barrios-Rebollo.

The results presented in this article have not been previously published in full or in part, except in abstract form (53rd Congress of the Spanish Society of Nephrology, November 2023; EuroPD Congress, November 2023).

References

1. Outerelo MC 4. Intraperitoneal pressure has a prognostic impact on peritoneal dialysis patients. Peritoneal Dialysis International. 2014;34(6):652–73.
2. Durand PY, Chanliau J, Gamberoni J, Hestin D, Kessler M. APD: Clinical measurement of the maximal acceptable intraperitoneal volume. Adv Perit Dial. 1994;10:63–7.
3. Betancourt L, Pico S, Rojas E, Gordo MJ, Oliva JC, Almirall J, et al. Relationship between intraperitoneal pressure and the development of hernias in peritoneal dialysis: confirmation for the first time of a widely accepted concept. Int Urol Nephrol. 2024 Feb 1;56(2):759–65.
4. Dejardin3 A, Robert A, Goffin E. Intraperitoneal pressure in PD patients: Relationship to intraperitoneal volume, body size and PD-related complications. Nephrology Dialysis Transplantation. 2007;22(5):1437–44.
5. Zhang J, Song L, Ma Z, Sun L, Wang X, Liu D, et al. Intra-abdominal pressure and residual renal function decline in peritoneal dialysis: a threshold-based investigation. Ren Fail. 2024;46(1).
6. Sastre A, González-Arregoces J, Romainoik I, Mariño S, Lucas C, Monfá E, et al. Factores de riesgo asociados a hernias en diálisis peritoneal. Nefrología. 2016 Sep;36(5):567–8.
7. Betancourt L, Ponz E, Grau C, Comas C, Vidiella J, Gordo MJ, et al. Prognostic value of high intraperitoneal pressure in patients on peritoneal dialysis. Int Urol Nephrol. 2025;
8. Fischbach M, Desprez P, Donnars F, Geisert J. Hydrostatic Intraperitoneal Pressure in Children on Peritoneal Dialysis: Practical Implications. An 18 Month Clinical Experience. Adv Perit Dial. 1994;10:294–6.

9. Yves Durand F, Chanliau J, Gamberoni J, Hestin D, Kessler M. Intraperitoneal Hydrostatic Pressure and Ultrafiltration Volume in CAPD [Internet]. 1993. Available from: https://www.advancesinpd.com/adv93/10pressure93.html

10. Pérez-Díaz V, Pérez-Escudero A, Sanz-Ballesteros S, Sánchez-García L, Hernández-García E, Oviedo-Gómez V, et al. Clinical relevance of marginal factors on ultrafiltration in peritoneal dialysis. Peritoneal Dialysis International. 2021 Jan 1;41(1):86–95.

11. Betancourt Castellanos L, Ponz Clemente E, Blasco Cabañas C, Marquina Parra D, Bolós Contador M, Oliva JC, et al. Clinical relevance of intraperitoneal pressure in peritoneal dialysis patients. Peritoneal Dialysis International. 2017;37(5):562–7.

12. Sobrino-Pérez A, Pérez-Escudero A, Sánchez-García L, Sanz-Ballesteros S, Felipe-Fernández C, Hernández-García E, et al. Clinical relevance of the impact of intraperitoneal pressure on ultrafiltration in the peritoneal equilibration test with 4.25%/3.86% glucose. Involvement of aquaporin function. Peritoneal Dialysis International. 2026.

13. Scanziani R, Dozio B, Baragetti I, Maroni S. Intraperitoneal hydrostatic pressure and flow characteristics of peritoneal catheters in automated peritoneal dialysis. Nephrology Dialysis Transplantation. 2003 Nov;18(11):2391–8.

14. Giuliani A, Milan Manani S, Crepaldi C, Domenici A, Gastaldon F, Corradi V, et al. Intraperitoneal Pressure in Polycystic and Non-Polycystic Kidney Disease Patients, Treated by Peritoneal Dialysis. Blood Purif. 2020 Nov 1;49(6):670–6.

15. Sigogne M, Kanagaratnam L, Mora C, Pierre M, Petrache A, Marcus C, et al. Identification of the Factors Associated With Intraperitoneal Pressure in ADPKD Patients Treated With Peritoneal Dialysis. Kidney Int Rep. 2020 Jul 1;5(7):1007–13.

16. Sanchez NC, Tenofsky PL, Dort JM, Shen LY, Helmer SD, Smith RS. What is normal intra-abdominal pressure? Am Surg. 2001;67(3):243–8.

17. Broers NJH, Canaud B, Dekker MJE, van der Sande FM, Stuard S, Wabel P, et al. Three compartment bioimpedance spectroscopy in the nutritional assessment and the outcome of patients with advanced or end stage kidney disease: What have we learned so far? Vol. 24, Hemodialysis International. Blackwell Publishing Inc.; 2020. p. 148–61.

18. Morelle J, Stachowska-Pietka J, Öberg C, Gadola L, La Milia V, Yu Z, et al. ISPD recommendations for the evaluation of peritoneal membrane dysfunction in adults: Classification, measurement, interpretation and rationale for intervention. Peritoneal Dialysis International. 2021 Jul 1;41(4):352–72.

19. Martin AD, Daniel MZ, Drinkwater DT, Clarys JP. Adipose tissue density, estimated adipose lipid fraction and whole body adiposity in male cadavers. Int J Obes Relat Metab Disord [Internet]. 1994 Feb;18(2):79–83. Available from: http://www.ncbi.nlm.nih.gov/pubmed/8148928

20. Fuller NJ, Jebb SA, Laskey MA, Coward WA, Elia M. Four-component model for the assessment of body composition in humans: comparison with alternative methods, and evaluation of the density and hydration of fat-free mass. Clin Sci. 1992 Jun 1;82(6):687–93.

21. Sobrino-Pérez A, Pérez-Escudero A, Fernández-Arroyo L, Dorado-García A, Martín-Alcón B, Gutiérrez-Martín C, et al. Intraperitoneal pressure: Stability over time and validation of Durand's measurement method. Peritoneal Dialysis International. 2021 Jul 1;41(4):427–31.

22. Costa IPD, Hautem N, Schiano G, Uchida S, Nishino T, Devuyst O. Fasting influences aquaporin expression, water transport and adipocyte metabolism in the peritoneal membrane. Nephrology Dialysis Transplantation. 2023 Jun 1;38(6):1408–20.

23. Wabel P, Chamney P, Moissl U, Jirka T. Importance of whole-body bioimpedance spectroscopy for the management of fluid balance. In: Blood Purification. 2009. p. 75–80.

24. Han BG, Lee JY, Kim JS, Yang JW. Clinical significance of phase angle in non-dialysis CKD stage 5 and peritoneal dialysis patients. Nutrients. 2018 Sep 19;10(9).

25. Cigarrán Guldris S, Ribera Polusa Rúa Iglesias Otero H. Presente y futuro de la bioimpedancia en la enfermedad renal [Internet]. Vol. 17. 2025. Available from: https://biorender.com/ftwds59.

26. Huang R, Wu M, Wu H, Ye H, Peng Y, Yi C, et al. Lower Phase Angle Measured by Bioelectrical Impedance Analysis Is a Marker for Increased Mortality in Incident Continuous Ambulatory Peritoneal Dialysis Patients. Journal of Renal Nutrition. 2020 Mar 1;30(2):119–25.

27. Abad S, Sotomayor G, Vega A, Pérez de José A, Verdalles U, Jofré R, et al. El ángulo de fase de la impedancia eléctrica es un predictor de supervivencia a largo plazo en pacientes en diálisis. Nefrologia. 2011;31(6):670–6.

28. Kang SH, Do JY. Phase Angle as a Risk Factor for Mortality in Patients Undergoing Peritoneal Dialysis. Nutrients. 2023 Dec 1;15(23).

29. Coca A, Arias-Cabrales C, Pérez-Sáez MJ, Fidalgo V, González P, Acosta-Ochoa I, et al. Impact of intra-abdominal pressure on early kidney transplant outcomes. Sci Rep. 2022 Dec 1;12(1).

30. Morelle J, Marechal C, Yu Z, Debaix H, Corre T, Lambie M, et al. AQP1 Promoter Variant, Water Transport, and Outcomes in Peritoneal Dialysis . New England Journal of Medicine. 2021 Oct 21;385(17):1570–80.

31. Bello AR, Bucalo L, Estébanez SA, Martínez AV, Núñez DB, Lozano CY, et al. Fat tissue and inflammation in patients undergoing peritoneal dialysis. Clin Kidney J. 2016 Jun 1;9(3):374–80.

32. Portolés J, Vega A, Lacoba E, López-Sánchez P, Botella M, Yuste C, et al. ¿Es adecuada la diálisis peritoneal para pacientes mayores de 65 años? Estudio multicéntrico prospectivo. Nefrología. 2021 Sep;41(5):529–38.

33. González E, Díez JJ, Pérez Torres A, Bajo MA, del Peso G, Sánchez-Villanueva R, et al. Composición corporal y concentraciones de adipocitoquinas en hemodiálisis: la ganancia de grasa abdominal como factor de riesgo cardiovascular añadido. Nefrología. 2017 Mar;37(2):138–48.

34. Verger C, Larpent L, Veniez G, Corvaisier B. Surveillance de la perméabilité du péritoine en dialyse péritonéale. Revue du Practicien. 1991;41(12):1086–90.

35. Kohaut E c., Bryson Waldo F, Benfield MR. The effect of changes in dialysate volume on glucose and urea equilibration. Peritoneal Dialysis International. 1994;14:236–9.

36. Fukuda M, Kawamura K, Kawahara K, Ohkawa T, Kamiyama Y, Honda M. Influence of instilled volume on the peritoneal equilibration test (PET). Peritoneal Dialysis International. 1994;14(4):406–7.

37. Keane D, Gardiner C, Lindley E, Lines S, Woodrow G, Wright M. Changes in body composition in the two years after initiation of haemodialysis: A retrospective cohort study. Nutrients. 2016 Nov 1;8(11).

38. Parthasarathy R, Oei E, Fan SL. Clinical value of body composition monitor to evaluate lean and fat tissue mass in peritoneal dialysis. Eur J Clin Nutr. 2019 Nov 1;73(11):1520–8.

39. Durand PY, Chanliau J, Gambéroni J, Hestin D, Kessler M. Intraperitoneal hydrostatic pressure and ultrafiltration volume in CAPD. Adv Perit Dial. 1993;9:46–8.

40. Fischbach M, Desprez P, Donnars F, Geisert J. Hydrostatic intraperitoneal pressure in children on peritoneal dialysis: practical implications. An 18-month clinical experience. Adv Perit Dial. 1994;10:294–6.

41. Flessner MF. Peritoneal ultrafiltration: physiology and failure. Contrib Nephrol. 2009;163:7–14.

42. Tinroongroj N, Jittikanont S, Lumlertgul D. Relationship between Malnutrition-Inflammation Syndrome and Ultrafiltration Volume in Continuous Ambulatory Peritoneal Dialysis Patients [Internet]. Vol. 91, J Med Assoc Thai. 2011. Available from: http://www.mat.or.th/journal

43. Pérez-Díaz V, Pérez-Escudero A, Sanz-Ballesteros S, Rodríguez-Portela G, Valenciano-Martínez S, Palomo-Aparicio S, et al. A new method to increase ultrafiltration in peritoneal dialysis: Steady concentration peritoneal dialysis. Peritoneal Dialysis International. 2016 Sep 1;36(5):555–61.

44. Kuriyama S, Otsuka Y, Iida R, Matsumoto K, Hosoya T. Icodextrin with small and short dwell enhances ultrafiltration in peritoneal dialysis patients with severe overhydration [2]. Peritoneal Dialysis International. 2006;26(4):508–9.

45. Konings CJAM, Kooman JP, Schonck M, Gladziwa U, Wirtz J, Van Den Wall Bake AW, et al. Effect of icodextrin on volume status, blood pressure and echocardiographic parameters: A randomized study. Kidney Int. 2003 Apr 1;63(4):1556–63.

46. Postaire O, Tournaire-Roux C, Grondin A, Boursiac Y, Morillon R, Schäffner AR, et al. A PIP1 aquaporin contributes to hydrostatic pressure-induced water transport in both the root and rosette of Arabidopsis. Plant Physiol. 2010;152(3):1418–30.

47. Maurel C, Boursiac Y, Luu DT, Santoni V, Shahzad Z, Verdoucq L. Aquaporins in Plants. Physiol Rev [Internet]. 2015 Oct;95(4):1321–58. Available from: https://www.physiology.org/doi/10.1152/physrev.00008.2015

48. Nguyen T, Toussaint J, Xue Y, Raval C, Cancel L, Russell S, et al. Aquaporin-1 facilitates pressure-driven water flow across the aortic endothelium. Am J Physiol Heart Circ Physiol [Internet]. 2015;308:1051–64. Available from: www.ajpheart.org

49. Toussaint J, Raval CB, Nguyen T, Fadaifard H, Joshi S, Wolberg G, et al. Chronic hypertension increases aortic endothelial hydraulic conductivity by upregulating endothelial aquaporin-1 expression. Am J Physiol Heart Circ Physiol [Internet]. 2017;313:1063–73. Available from: www.ajpheart.org